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13. ABSTRACT *(Maximum 200 words)*

This final technical report contains a summary and highlights of the research funded by AFOSR under Grant F49620-92-J-0261, titled "Computational Methods for Control and Optimal Design of Aerospace Systems (FY 91 AASERT)", for the period 1 June 1992 to 31 May 1995. This AASERT grant supported two graduate students to work on the following topics; (i) the development of shape optimization algorithms for flow tailoring with applications to the design of forebody simulators, and (ii) control of fluid/structure interactions. A new sensitivity equation method was developed and integrated into an optimization package for optimal design and flow tailoring. This method was transitioned into software packages at several industrial and government sites. In addition, this research produced a new understanding of the role that dissipation plays in optimization based design. and produced a new framework to analyze convergence of algorithms based on approximations of sensitivity equations. The report contains a summary of these results and a list of papers produced during this period.

14. SUBJECT TERMS

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FINAL TECHNICAL REPORT

1. INTRODUCTION AND OBJECTIVES

This project was funded through an AASERT grant and supported two graduate students (Jeffrey Borggaard and John Burkardt) to work with Professors John A. Burns and Max Gunzburger (currently supported under AFOSR Grant F49620-93-1-0280) on computational methods for optimal design. Dr. Borggaard was supported from 1 June 1992 to 15 December 1994 and Dr. Burkardt was supported from 1 January 1995 to 31 May 1995. The effort concentrated on several problems involving the development and analysis of computational algorithms for optimal design of fluid flows. This research project had the following specific objectives:

- To develop and analyze mathematical and computational methods for optimal design of fluid flows. Although the research is centered around joint effort with AEDC scientists, the primary goal of this effort was the development of general tools for application to a broad spectrum of optimal design problems of interest to DOD.

- To work with Air Force Facilities and industry to transition this research and to use Air Force problems as test models for computational experiments.

A forebody design problem has played a central role in the research program. This application was used to motivate the basic research, as a test case for computational experiments and as mechanisms to transition the research into Air Force facilities and industry. In addition, over the course of this grant several optimal control and design problems were studied and new computational methods were developed for general classes of problems.

2. ACCOMPLISHMENTS

The project objectives were all accomplished and both students supported under this grant completed their Ph.D. during the final year of the contract. In addition to the development of computational methods, basic theoretical issues were addressed and fundamental understanding of these systems were obtained through a combined

computational and theoretical analysis. This work established the feasibility of the **SEM** method as a practical design tool, produced software for various industrial and Air Force applications and demonstrated several new techniques for control design and optimization. In addition, several companies are now in the process of upgrading their software to include a design sensitivity module based on the research conducted under this grant.

Summary of Accomplishments

During this three year period Dr. Borggaard and Dr. Burkardt made significant progress on their projects. In particular, they:

- **Completed two dissertations**

    Jeff Borggaard, "The Sensitivity Equation Method for Optimal Design", Ph.D. Thesis, December, 1994, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24060

    John Burkardt, "Sensitivity Analyses and Computational Shape Optimization for Incompressible Flows", Ph.D. Thesis, May 1995, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24060.

- **Produced 12 research papers**

- **Gave 34 scientific lectures on research supported under this grant**

- **Developed a new computational approach to optimal design**

- **Identified fundamental new issues in the area of optimal design**

- **Gave a rigorous proof of convergence for the SEM for problems with shocks**

- **Investigated finite element approximations of sensitivity equations for flows**

Research Highlights

The following paragraphs provide a detailed description of the accomplishments made under this grant. The work resulted in two Ph.D. dissertations and 10 research papers. The work described below concerns the research conducted by Dr. Borggaard and Dr. Burkardt.

The Optimal Forebody Design Problem - The Air Force Arnold Engineering Development Center (AEDC) is responsible for the development of facilities and tools for testing integrated propulsion systems (i.e., engines, inlets and airframes). Since many full-

scale propulsion systems are too large for the largest ground facility, the AEDC investigated a free-jet test technique for use in the Aeropropulsion System Test Facility (ASTF). This technique permits full-scale engines to be tested with real inlets and forebody simulators (FBS). A forebody simulator is a physical device attached to the engine. The purpose of the FBS is to produce a flow field at the inlet that approximates the actual aircraft forebody effects in flight. In a free-jet test, the engine, inlet and forebody simulator are placed in a test section and a free-jet nozzle is employed to control the flow over the test article in order to simulate angle-of-attack and sideslip effects. The goal of this test configuration is to produce (i.e., control) the flow field at the engine inlet that is approximately the same flow field produced by the total aircraft in free flight. A complete description of this problem and the AEDC program may be found in [2], [3], [13], [14] and the references therein.

One needs to design an FBS that produces the inlet flow of the real aircraft to be tested. The shape of the FBS is to be determined so as to minimize the "distance" between the flow generated by the FBS and the desired flow conditions. There are several possible approaches to this problem, but initially AEDC considered two basic methods for attacking this type of "shape optimization" problem. The first is a trial-and-error approach and is done using empirical design techniques. The second approach is based on "black-box" optimization methods. In particular, it is a method that combines numerical optimization with computational fluid dynamics to produce an optimal design capability. The joint ASD/AEDC Aeropropulsion System Test Facility Free-Jet Development Technical Steering Committee proposed that such an optimization-based design technique be developed to solve the FBS design problem. This initial problem was the primary motivation for the research conducted by both Dr. Borggaard and Dr. Burkardt.

Sensitivity Equation Method (SEM) for Optimal Design - Initially the FBS optimization based design program at AEDC was a block-box method that combined the output of a CFD code (PARC3D or PARC2D) developed at AEDC with existing Gauss-Newton or quasi-Newton algorithms to produce sub-optimal designs. Gradients were computed by finite-differences. This procedure requires that the CFD code be "fully converged" in order to obtain "accurate" gradients. Consequently, the computational work required for each gradient evaluation is extremely large and the number of control and design variables must be kept small. This was an inhibiting factor in the development of a more practical optimization based design capability. Better methods were needed to compute sensitivities for the optimization loops. Existing techniques (based on finite differences) produced inaccurate sensitivities and were computationally expensive. In the papers [2] and [3] we developed a *Sensitivity Equation Method* (SEM) approach to this problem. This approach allows us to compute the sensitivities without using finite differences. An optimal design algorithm based on the SEM combined with a trust region optimization algorithm was used to test this approach on a 2D version of the optimal forebody design problem. We observed faster and more robust convergence for this computational scheme and we are continuing to refine this idea. In addition, this approach seems to improve as the number of design parameters increased due to vectorization and parallelism.

This method was transitioned into a number of software packages. We have adapted the PARC2D code and it now contains a sensitivity module based on the **SEM**. Also, AEDC engineers have made considerable progress in adapting the PARC code so that the sensitivities can be computed by this new technique. Moreover, Dr. Borggaard assisted in the development of a SEM module for Beam Technologies. These projects will be continued under the support of the Air Force Center for Optimal Design and Control (**CODAC**).

Dissipation study in the 2D Forebody Design Problem - This research produced a new understanding of the role that dissipation plays in optimization based design. Contrary to intuition, the use of "shock capturing" schemes in optimal design problems with shocks can produce inaccurate and, in some cases, incorrect optimal designs. The use of such schemes can produce artificial local minima that causes the optimization algorithm to become trapped and unable to find the global minimum. In particular, an analysis of a one dimensional Euler flow duct design problem [1] clearly demonstrated this phenomenon. In fact, an optimization problem was constructed which failed to predict the global minimum since it predicted an "optimal" duct shape which was a local minima of the approximate cost functional. This minima of the approximate cost functional was clearly not a minima of the original infinite dimensional duct design problem.

The 1D study prompted another investigation into the 2D problem to determine the effect of dissipation on the Forebody design problem that uses AEDC's PARC2D Euler solver. Numerical dissipation was introduced by varying finite difference mesh sizes and the artificial viscosity parameter used for numerical stability. We performed a forebody optimization on a coarse mesh and then used the predicted forebody parameters as an initial guess for optimization on a fine mesh. The results showed that the inaccuracies produced by the coarse mesh actually lead to poor initial guesses. In some instances, the coarse mesh forebody parameters would produce a forebody shape that could not be solved using a fine mesh.

When changing the artificial viscosity parameter, we found little improvement in the speed of the optimization procedure. However, the inaccuracies in the resulting flow analysis produced slightly different forebody parameters that tested as sub optimal when tested using the standard artificial dissipation setting.

As a result of this effort we now know that in black-box approaches to optimal design, the combination of simulation and optimization packages must be done carefully. Certain "shock capturing" schemes that are excellent "simulators" can produce inaccurate and, in some cases, incorrect designs when applied to optimal design problems with shocks. Numerical and artificial viscosity will often eliminate these artificial local minima and hence the optimization algorithm will perform better. However, there is a price to be paid with accuracy and speed. Therefore, in order to avoid such problems we developed a new hybrid scheme that uses dissipation as a control to steer an optimization algorithm to a neighborhood of a global minimum and then switches to a high order shock fitting

scheme to refine the optimal design.

Nozzle Model Design Problem - Based on discussions between researchers at **CODAC** and the AEDC engineers, it was determined that AEDC had an interest in using optimal design techniques in designing nozzles. In particular, there was interest in creating a set of test sections that could be interchanged depending on what wind tunnel flow configuration is desired. As a consequence, a presentation of the Sensitivity Equation Method for optimal design was given which included an example where parameters representing a nozzle section of fixed length were optimized to produce a given outflow profile.

Alternative methods were investigated for solving nozzle design problems that would avoid the shock problem discussed in [1]. Consulting with Lucien Polak, we investigated a Sequential Quadratic Programming (SQP) approach where the shock location is considered as another design variable and the Rankine-Hugoniot condition is viewed as a constraint. A standard black-box implementation of this lead to similar local minimum problems as found using the quasi-Newton black-box approach. However, it may be possible to use the sensitivity equation to determine good approximate gradients of the exact cost functional. More work on this method is planned.

Solution of the Sensitivity Equations for the 1D Euler Equations - As pointed out in [1] and [3] the sensitivity equations for the Euler equations are linear in the sensitivity variable. Therefore, substantial savings could be achieved if one could solve the linear equation by some other method than that used to solve the original nonlinear system. One difficulty, however, is that the linear equation has discontinuous coefficients. In fact, where the original equation is hyperbolic (for boundary conditions that are of interest), the coupled system of state equation and sensitivity equation turns out to be non strictly hyperbolic. The availability of solvers for systems of this type is unknown. We tried using standard techniques for solving hyperbolic equations (Godunov, Enquist-Osher and Artificial Viscosity methods) to solve these equations. The initial findings were mixed. A solution to the sensitivity equations was found in 25% of the time required to solve the state equation. However, the points that lie in the shock region had unreasonable solutions while the points outside of this region were predicted accurately. This problem was solved by modifying the numerical schemes used to solve the sensitivity equation. One approach considered near the end of the project was to use finite element techniques to generate solutions of the sensitivity equations. This work is documented in Burkardt's dissertation [13] and papers [11] and [12].

Solution of the Sensitivity Equations for Incompressible Flows - As pointed out above the basic advantage of the **SEM** is that one can obtain cheap approximate solutions of the exact sensitivity equations. However, discretized sensitivities are only an approximation to the sensitivities of the discrete solution which are needed in the finite dimensional optimization problem. Thus it becomes necessary to determine the error introduced by the approximation process and then determine if the trust region optimization converges when these approximate sensitivities are used for gradients. Dr. Burkardt was able to show that the SEM was still a viable approach to viscous flows for

moderate Reynolds numbers. However, he also observed cases where the finite element method produced unusable approximate sensitivities. This work shows the need to develop error estimates for the difference between finite element approximations of sensitivities and the sensitivities of corresponding finite element models. In particular, it is necessary to examine standard algorithms used for solving forward systems and see which algorithms are appropriate for solving the corresponding sensitivity equations. For certain conservation laws, Borggaard was able to establish the consistency and stability of standard finite difference approximations (see [7] and [14]).

New Theory of Asymptotically Consistent Gradients - Several issues have been raised concerning the use of so-called "consistent derivatives" in numerical algorithms for optimal design. The SEM does not use consistent derivatives and has been shown to be very successful for the forebody optimization problem. However, to understand the success of this method it became necessary to develop a theoretical framework to analyze the convergence. Dr. Borggaard developed this theory in [7] and [14] and applied it to the 1D duct problem and a hyperbolic system. The key is to use a robust optimizer to allow for gradient errors. Thus trust region methods seem to be a good choice for an optimization algorithm when used in black-box type methods. Although the basic framework has been developed, much work remains before a complete theory can be constructed.

3. RESEARCH PUBLICATIONS

The following papers were produced by Dr. Borggaard and Dr. Burkardt under this grant:

1. Borggaard, J., "On the Presence of Shocks in Domain Optimization of Euler Flows", Proc. IMA Workshop on Fluid Flow Control, M. Gunzburger, Ed., Springer-Verlag, 1995, 35-48.

2. Borggaard, J. and Burns, J., "A Sensitivity Equation Approach to Shape Optimization in Fluid Flows", Proceedings of the IMA Conference on Fluid Flow Control, M. Gunzburger, Ed., Springer-Verlag, 1995, 49-78.

3. Borggaard, J., Burns, J., Cliff, E. and Gunzburger, M. "Sensitivity Calculations for a 2D, Inviscid, Supersonic Forebody Problem", Proceedings AMS-IMS-SIAM 1992 Summer Conference on Distributed Parameter Control, Banks, H.T., Fabiano, R.H. and Ito, K., Eds., SIAM Publications, 1993, 14-25.

4. Borggaard, J., Herdman, T. and Turi, J., "On Control Design for a Fluid-Structure Interaction Problem", Proceedings of the First IEEE Regional Conference on Aerospace Control Systems, May 1993, 236-242.

5. Borggaard, J. and Burns, J., "A Sensitivity Equation Approach for the Optimal Design of Nozzles", AIAA 5th Symposium on Multidisciplinary Analysis and Optimization, September, 1994, 232-241.

6. Borggaard, J., Herdman, T. and Turi, J., "On an Application of the Boundary Element Method to Study Flow Induced Vibrations", <u>Applied Mechanics in the Americas</u>, L.A. Godoy, S.R. Idelsohn, P.A.A. Laura and D.T. Mook, Eds., Vol 2, Sante Fe, Argentina, January 1995, 317-321.

7. Borggaard, J. and Burns, J., "Asymptotically Consistent Gradients in Optimal Design", <u>Proceedings of the Workshop on Multidisciplinary Design Optimization</u>, N. Alexandrov, Ed., SIAM, to appear.

8. Borggaard, J., Herdman, T. and Turi, J., "On Active Control of Flow Induced Vibrations", <u>Proceedings of the 34th IEEE Conference on Decision and Control</u>, to appear.

9. Borggaard, J. and Pelletier, D., "Computing Design Sensitivities Using an Adaptive Finite Element Method", <u>27th AIAA Fluid Dynamics Conference</u>, submitted.

10. Borggaard, J., Burkardt, J., Burns, J., Cliff, E., Gunzburger, M., Kim, H., Lee, H., Peterson, J., Shenoy, A. and Wu, X., "Algorithms for Flow Control and Optimization", <u>Optimal Design and Control</u>, J. Borggaard, J. Burkardt, M. Gunzburger and J. Peterson, Eds., Progress in Systems and Control Theory, Volume 19, Birkhaeuser, 1994, 97-116.

11. John Burkardt and Janet Peterson, "Control of Steady Incompressible 2D Channel Flow", Flow Control, The IMA Volumes in Mathematics and Its Applications, Volume 68, Springer-Verlag, New York, 1995.

12. John Burkardt and Janet Peterson, "The Role of the Cost Functional in a Shape Optimization", Computation and Control IV, Proceedings of the Fourth Bozeman Conference on Computation and Control, Progress in Systems and Control Theory, Birkhaeuser, 1995.

13. John Burkardt, "Sensitivity Analyses and Computational Shape Optimization for Incompressible Flows", Ph.D. Thesis, May 1995, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24060.

14. Jeff Borggaard, "The Sensitivity Equation Method for Optimal Design", Ph.D. Thesis, December, 1994, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24060

Edited Workshop Volume:

Optimal Design and Control, J. Borggaard, J. Burkardt, M. Gunzburger and J. Peterson, Eds., Progress in Systems and Control Theory, Volume 19, Birkhaeuser, 1994.

4. PROFESSIONAL PERSONNEL

Principal Investigator

J. A. Burns

Graduate Students

Jeffrey Borggaard
John Burkardt

5. INTERACTIONS

Talks, Lectures and Conferences

Jeffrey Borggaard

1. IEEE Conference on Aerospace Control Systems, Westlake, CA, June,1993

2. University of Texas at Dallas, Richardson, Texas, June, 1993

3. Attended the SIAM Annual Meeting, July, 1993

4. Arnold Engineering Development Center, Tullahoma, TN, "The Use of the SEM in Optimal Design", September, 1993

5. Attended the Matlab Conference, Boston, MA, September, 1993

6. IMA Workshop on Flow Control, Minneapolis, MN, November, 1993.

7. AIAA 5th Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

8. Oregon State University, Mathematics Department Colloquium, Corvallis, OR, February, 1995.

9. SIAM Annual Meeting, Charlotte, NC, October, 1995.

10. AMS Fall Southern Sectional Meeting, Greensboro, NC, November, 1995.

11. 34th IEEE Conference on Decision and Control, New Orleans, LA, December, 1995.

12. 27th AIAA Fluid Dynamics Conference, New Orleans, LA, June, 1996 (pending).

John Burkardt

1. IMA Workshop on Flow Control, Minneapolis, MN, November, 1993.

2. SIAM Annual Conference, Philadelphia, Pennsylvania, April 1994.

3. Fourth International Conference on Computation and Control, Bozeman, Montana, August 1994.

4. ASME Forum on CFD for Design and Optimization, San Francisco, California, November 1995.

J.A. Burns

1. IEEE Conference New Directions in Control, Crete, Greece, June, 1993

2. AIAA Shear Flow Control Conference, Orlando, FL, July, 1993

3. National SIAM Meeting, Philadelphia, PA, July, 1993

4. Sixth International Conference on Distributed Parameter Control, Vorau, Austria, July 1993

5. International Conference on Mathematical Theory of Networks and Systems, Regensburg, Germany, July 1993

6. SIAM Conference on Linear Algebra, Systems and Control, Seattle, WA, August, 1993

7. Montana State University, Bozeman, MT, October, 1993.

8. Tektronix Printing and Ink Division, Wilsonville, OR, January, 1994

9. University of Minnesota, Minneapolis, MN, February, 1994.

10. Air Force Conference on Dynamics and Control, Dayton, OH, June, 1994.

11. Center for Research on Computation and its Application, Montreal, Quebec,

September 1994

12. National SIAM Meeting, San Diego, CA, July, 1994.

13. Fourth International Conference on Computation and Control, Bozeman, MT, August 1994.

14. Oregon State University, Corvallis, OR, October, 1994

15. IEEE Conference on Decision and Control, Orlando, FL, December 1994.

16. ICASE/LaRC Multidisciplinary Design Optimization Workshop, Hampton, VA, March, 1995.

17. SPIES Conference on Sensing and Control of Aerosystems, Orlando, FL, April 1995.

18. SIAM Conference on Control, St. Louis, MO, April 1995.

Laboratory and Industrial Interactions

In addition to the research described above, during the grant period we had the following interactions with Air Force personnel and industries.

Air Force Arnold Engineering Development Center, Tullahoma, TN
    Captain Scott Tennent
    Captain Mark Briski

Sverdrup Company, Tullahoma, TN
    Mr. Donald Todd
    Mr. Karl Kneile

CALSPAN Company, Tullahoma, TN
    Dr. John Benek
    Dr. Peter Hoffman
    Dr. Steve Keeling

BEAM Technologies, Ithaca, NY
    Dr. Gal Berkooz
    Dr. Richard Newsome